Mass Spectrum and Dark Matter in the CSE$_6$SSM

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New Directions in Subatomic Physics

The MSSM

- MSSM at tree-level: $m_{h_1}^2 \leq M_Z^2 \cos^2 2\beta \lesssim (91 \text{ GeV})^2$
- $m_{h_1} \approx 125.09$ GeV $\Rightarrow$ large higher order corrections

$$m_{h_1}^2 \approx M_Z^2 \cos^2 2\beta \left(1 - \frac{3}{8\pi^2} \frac{m_t^2}{v^2} \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{M_t^2}\right) + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{M_t^2} + \ldots$$

- $\Rightarrow$ also large corrections to prediction for M_Z at SUSY scale M_S:

$$\frac{M_Z^2}{2} = -\mu^2 + \frac{\overbrace{m_{H_d}^2 - m_{H_u}^2}^{\text{RGE effects}} \tan^2\beta}{\tan^2\beta - 1} + \delta_{1-\text{loop}},$$

$$\delta_{1-\text{loop}} = \frac{3}{8\pi^2} \frac{m_t^2}{v^2 \cos 2\beta} \left[m_{\tilde{t}_1}^2 \left(\ln \frac{m_{\tilde{t}_1}^2}{M_S^2} - 1 \right) + m_{\tilde{t}_2}^2 \left(\ln \frac{m_{\tilde{t}_2}^2}{M_S^2} - 1 \right) \right] + \ldots$$

- $\Rightarrow$ Little Hierarchy Problem
- $\mu-$problem: $M_Z^2 = -\mu^2 + \ldots \Rightarrow \mu \sim$ soft parameters?

Solving the Little Hierarchy Problem?

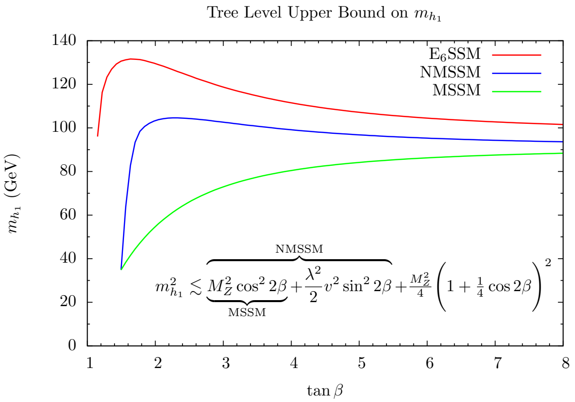
- Additional F-terms from new fields, e.g. NMSSM:

$$W \supset \lambda \hat{S} \hat{H}_d \cdot \hat{H}_u$$

- Additional D-terms from extended gauge sector, e.g. $U(1)$ extensions:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \\ \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$$

- Care required (anomaly cancellation)



E_6 Inspired Models

- Can arise from $E_8 \times E_8'$ heterotic string theory
- Low-energy models have extra $U(1)$ coming from breakdown

$$\begin{aligned} E_6 &\longrightarrow SO(10) \times U(1)_\psi \\ &\longrightarrow SU(5) \times U(1)_\psi \times U(1)_\chi \\ &\longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\psi \times U(1)_\chi \\ &\longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)' \end{aligned}$$

- Resulting $U(1)' = U(1)_\chi \cos\theta_{E_6} + U(1)_\psi \sin\theta_{E_6}$
- Matter content fills complete $\mathbf{27}$ representations
  - $\Rightarrow$ anomaly cancellation guaranteed
  - Exotic states at low-energies (extra scalars + vector-like fermions, anyone?)
- Break $U(1)'$ with singlet $\Rightarrow$ dynamically generate μ term, massive Z'

The E$_6$SSM

- Additional $U(1)_N$ under which right-handed neutrinos are uncharged ($\theta_{E_6} = \arctan\sqrt{15}$)
- Extra $\hat{L}_4$, $\hat{\overline{L}}_4$ from incomplete $\mathbf{27}'$, $\overline{\mathbf{27}}'$ for gauge unification
- Low-energy matter content from $\mathbf{27}$-plet:

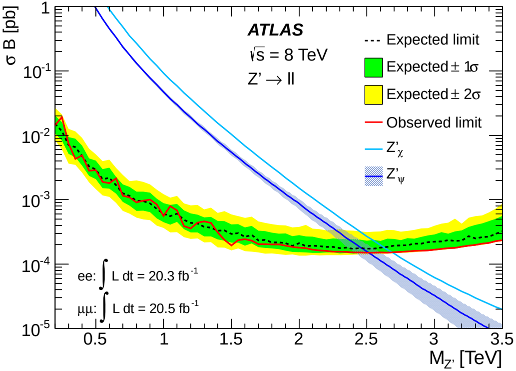
$$(\hat{Q}_i,\, \hat{u}^c_i,\, \hat{d}^c_i,\, \hat{L}_i,\, \hat{e}^c_i) + (\hat{D}_i,\, \hat{\overline{D}}_i) + (\hat{S}_i) + (\hat{H}^u_i) + (\hat{H}^d_i)$$

- Higgs doublets $\hat{H}^d_3 \equiv \hat{H}_d$, $\hat{H}^u_3 \equiv \hat{H}_u$ and one singlet $\hat{S}_3 \equiv \hat{S}$ get VEVs ($\Rightarrow$ EWSB and break $U(1)_N$)

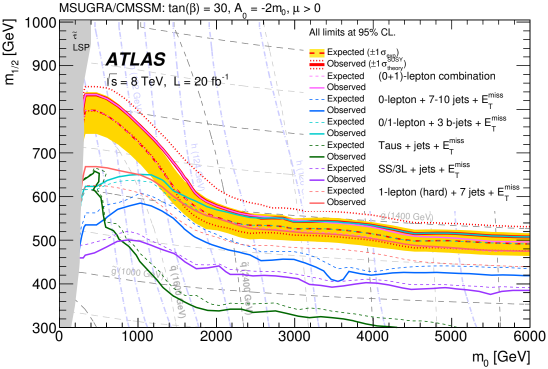
	$SU(3)_C$	$SU(2)_L$	$\sqrt{\frac{5}{3}}Q^Y_i$	$\sqrt{40}Q^N_i$
$\hat{Q}_i$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	1
$\hat{u}^c_i$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	1
$\hat{d}^c_i$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	2
$\hat{L}_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	2
$\hat{e}^c_i$	$\mathbf{1}$	$\mathbf{1}$	1	1
$\hat{S}_i$	$\mathbf{1}$	$\mathbf{1}$	0	5
$\hat{H}^u_i$	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	-2
$\hat{H}^d_i$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-3
$\hat{D}$	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	-2
$\hat{\overline{D}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	-3
$\hat{L}_4$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	2
$\hat{\overline{L}}_4$	$\mathbf{1}$	$\overline{\mathbf{2}}$	$\frac{1}{2}$	-2

$$W_{\text{E}_6\text{SSM}} \approx y_\tau \hat{L}_3 \cdot \hat{H}_d \hat{e}^c_3 + y_b \hat{Q}_3 \cdot \hat{H}_d \hat{d}^c_3 + y_t \hat{H}_u \cdot \hat{Q}_3 \hat{u}^c_3 + \lambda_i \hat{S} \hat{H}^d_i \cdot \hat{H}^u_i + \kappa_i \hat{S} \hat{D}_i \hat{\overline{D}}_i + \mu' \hat{L}_4 \cdot \hat{\overline{L}}_4$$

E$_6$SSM: $M_{Z'} \sim M_S$



[PRD 90 (2014) 052005 (arXiv:1405.4123)]

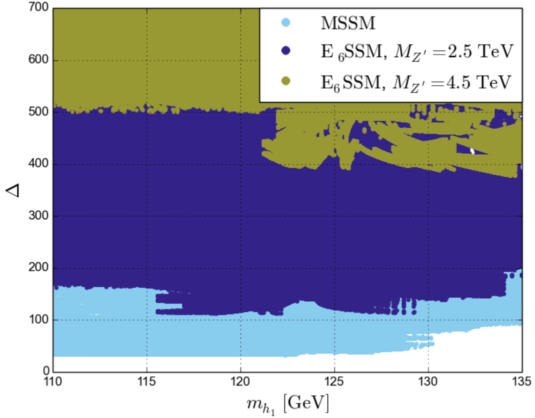


[JHEP 10 (2015) 054 (arXiv:1507.05525)]

Issues in the E_6SSM

$$\underbrace{c(\tan\beta)}_{O(1)}\frac{M_Z^2}{2} \approx -\lambda^2\langle S\rangle^2 + \frac{m_{H_d}^2 - m_{H_u}^2\tan^2\beta}{\tan^2\beta - 1} + d(\tan\beta)\frac{M_{Z'}^2}{2}$$

- Extra D-terms cut both ways
- $M_{Z'} \gtrsim 2.5$ TeV $\Rightarrow$ another large contribution must cancel
- Unnatural or fine-tuned? E.g. as measured using traditional measure of fine-tuning
- Also, dangerous B, L violating interactions $\Rightarrow$ need approximate Z_2^H + exact $Z_2^{L/B}$
- DM in simplest versions of model requires *another* exact Z_2^S



[PRD 91 (2015) 115024 (arXiv:1503.08929)]

The SE_6SSM

- Modification of E_6SSM, arising from 5D or 6D orbifold GUT [1]
- Low-energy matter content augmented by components of extra $\mathbf{27}'$, $\overline{\mathbf{27}}'$-plets, including:
  - doublets $\hat{H}_u$, $\hat{H}_d$ (note: now not from $\mathbf{27}$-plet)
  - singlets $\hat{S}$, $\hat{\overline{S}}$ with opposite $U(1)_N$ charges
- Still potentially dangerous B, L violating interactions
- But now can forbid using single, exact discrete $\tilde{Z}_2^H$
- Stabilise scalar potential $\Rightarrow$ pure singlet $\hat{\phi}$

$$
\begin{aligned}
W_{\mathsf{SE_6SSM}} = {} & \lambda\hat{S}(\hat{H}_d\cdot\hat{H}_u) - \sigma\hat{\phi}\hat{S}\hat{\overline{S}} + \frac{\kappa}{3}\hat{\phi}^3 + \frac{\mu}{2}\hat{\phi}^2 \\
& + \Lambda_F\hat{\phi} + \lambda_{\alpha\beta}\hat{S}(\hat{H}^d_\alpha\cdot\hat{H}^u_\beta) + \kappa_{ij}\hat{S}\hat{D}_i\hat{\overline{D}}_j \\
& + \tilde{f}_{i\alpha}\hat{S}_i(\hat{H}_u\cdot\hat{H}^d_\alpha) + f_{i\alpha}\hat{S}_i(\hat{H}^u_\alpha\cdot\hat{H}_d) \\
& + g^D_{ij}(\hat{Q}_i\cdot\hat{L}_4)\hat{\overline{D}}_j + h^E_{i\alpha}\hat{e}^c_i(\hat{H}^d_\alpha\cdot\hat{L}_4) \\
& + \mu_L(\hat{L}_4\cdot\hat{\overline{L}}_4) + \tilde{\sigma}\hat{\phi}(\hat{L}_4\cdot\hat{\overline{L}}_4) \\
& + W_{\mathsf{MSSM}}(\mu=0)
\end{aligned}
$$

[1] R. Nevzorov, Phys. Rev. **D** 87, 015029 (2013) (arXiv:1205.5967)

Dark Matter Candidates

	$\hat{Q}_i$	$\hat{u}^c_i$	$\hat{d}^c_i$	$\hat{L}_i$	$\hat{e}^c_i$	$\hat{N}^c_i$	$\hat{S}$	$\hat{\overline{S}}$	$\hat{S}_i$	$\hat{H}_u$	$\hat{H}_d$	$\hat{H}^u_\alpha$	$\hat{H}^d_\alpha$	$\hat{D}_i$	$\hat{\overline{D}}$	$\hat{L}_4$	$\hat{\overline{L}}_4$
$\tilde{Z}_2^H$	-	-	-	-	-	-	+	+	-	+	+	-	-	-	-	+	+
Z_2^M	-	-	-	-	-	-	+	+	+	+	+	+	+	+	+	-	-
Z_2^E	+	+	+	+	+	+	+	+	-	+	+	-	-	-	-	-	-

- Symmetry breaking pattern $\Rightarrow$ automatically conserved $Z_2^M = (-1)^{3(B-L)}$ ($\equiv$ R-parity)
- Per MSSM, implies stable DM candidate (typically $\tilde{\chi}_1^0$)
- Write $\tilde{Z}_2^H = Z_2^M \times Z_2^E \Rightarrow$ exotic Z_2^E also conserved
- Lightest exotic (Z_2^E odd) state is also stable DM candidate
- Very light inert singlinos form hot DM, but negligible contribution to relic density
- $\therefore$ relic density almost entirely due to ordinary neutralino

EWSB in the SE$_6$SSM

- E$_6$SSM: EWSB conditions $\Rightarrow M_{Z'} \sim M_S$ (i.e. $\langle S \rangle \sim M_S$)
- At physical minimum,

$$\langle H_d^0 \rangle = \frac{v_1}{\sqrt{2}} , \quad \langle H_u^0 \rangle = \frac{v_2}{\sqrt{2}} , \quad \langle S \rangle = \frac{s_1}{\sqrt{2}} , \quad \langle \overline{S} \rangle = \frac{s_s}{\sqrt{2}} , \quad \langle \phi \rangle = \frac{\varphi}{\sqrt{2}}$$

- S, $\overline{S}$ VEVs develop along nearly D-flat direction $\langle S \rangle = \langle \overline{S} \rangle$ with

$$\langle S \rangle \approx \langle \overline{S} \rangle \sim \frac{M_S}{\sigma}$$

- Small $\sigma \Rightarrow M_{Z'}^2 \sim g_1'^2 Q_S^2 (s_1^2 + s_2^2)$ far heavier than M_S
- $\therefore$ can have $M_{Z'}$ far above limits while keeping sparticles (relatively) light
- Note: also suppress D-term contribution to EWSB scale, i.e. M_Z^2

The CSE$_6$SSM

- General model is complicated
  - $O(200)$ new parameters (assuming no new sources of CP-violation)
  - Many masses and mixings
- Consider constrained model (CSE$_6$SSM) inspired by gravity mediated SUSY breaking
- Universal soft breaking parameters: $M_{1/2}$, A_0, B_0, m_0
- Want Z' mass decoupled from EWSB conditions $\Rightarrow$ fix heavy $s = \sqrt{s_1^2 + s_2^2} = 650$ TeV
- Suitable DM candidate $\Rightarrow$ small μ_{eff}, i.e. small λ
- Exotic $\lambda_{\alpha\beta}$, κ_i, ... free, but small λ $\Rightarrow$ natural for these to be small also
- FlexibleSUSY $\Rightarrow$ mass spectrum at full one-loop level, including full two-loop RGEs
  - In general, want to use automated tools for studying with high precision

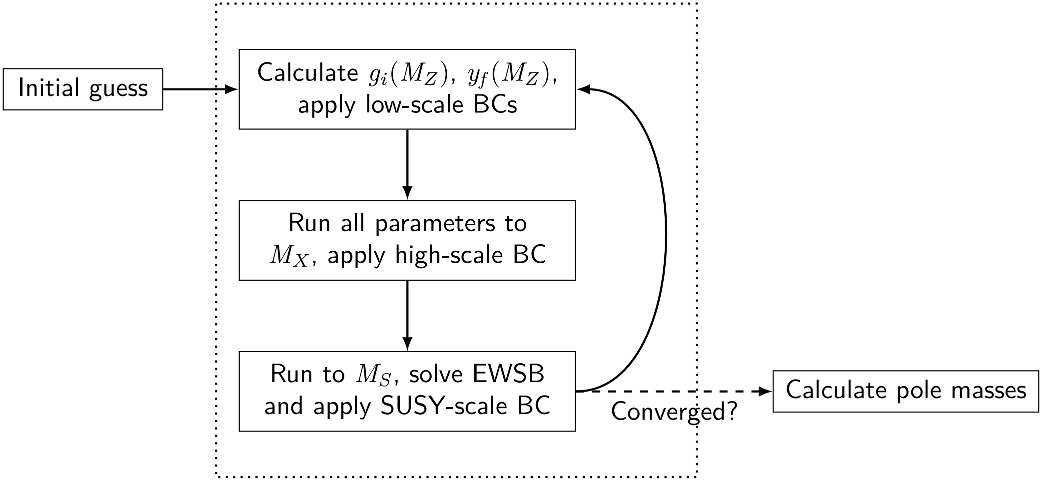
Semi-analytic Solutions

- Useful technique for studying constrained models (e.g. CE_6SSM)
- RGEs for SUSY parameters independent of soft SUSY breaking parameters (up to effects of threshold corrections)
- Treat RGEs for SUSY breaking parameters as system of linear ODEs
- Combine with boundary conditions $\Rightarrow$ semi-analytic solutions,

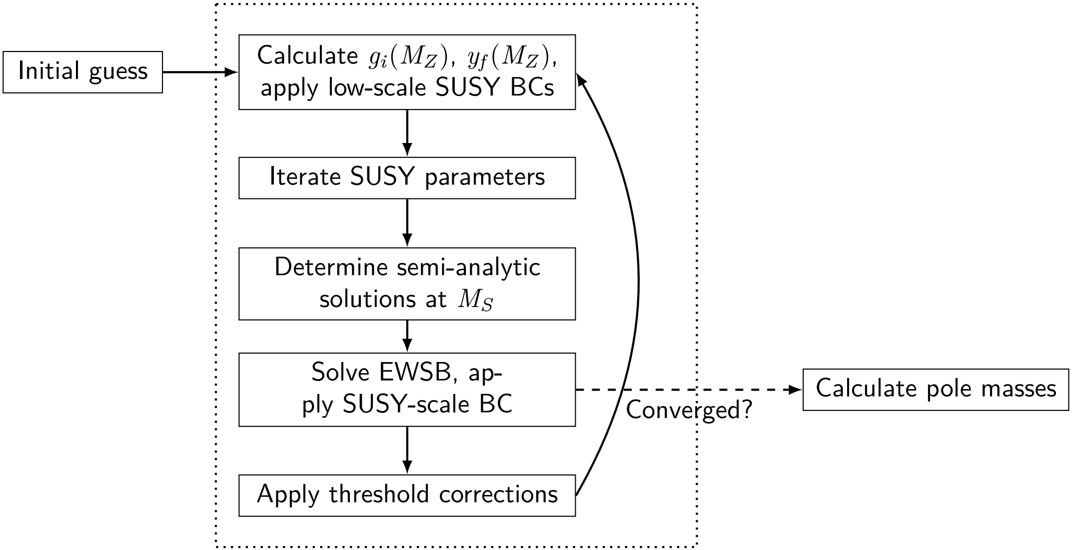
$$M_i(Q) = p_i(Q) M_{1/2} + q_i(Q) A_0 \, , \quad A_i(Q) = e_i(Q) A_0 + f_i(Q) M_{1/2} \, ,$$
$$m_i^2(Q) = a_i(Q) m_0^2 + b_i(Q) M_{1/2}^2 + c_i(Q) A_0 M_{1/2} + d_i(Q) A_0^2 \, , \ldots$$

- Coefficients depend only on SUSY parameters, calculated numerically
- Relate SUSY scale parameters to high-scale inputs, e.g. trade m_0 for μ_{eff}
  - Contrast with e.g. CMSSM: μ output for given m_0

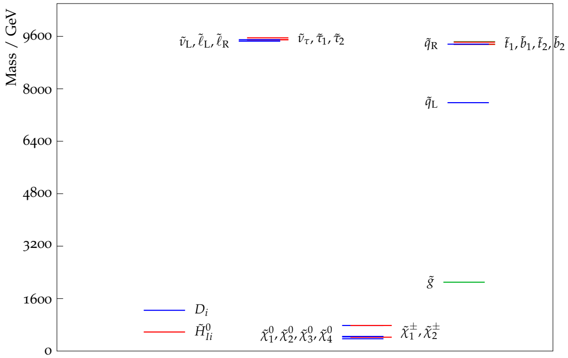
Two-scale Algorithm



Semi-analytic Algorithm

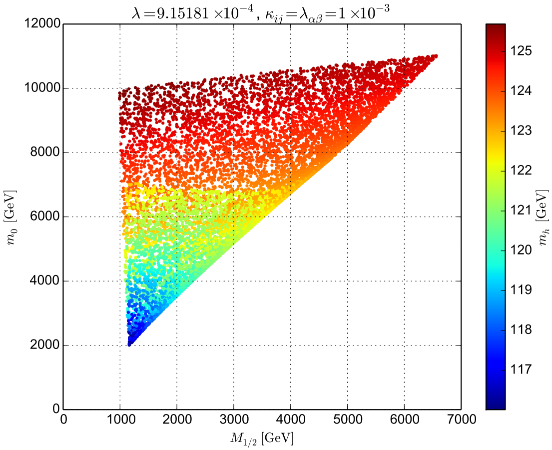


Sparticle Masses



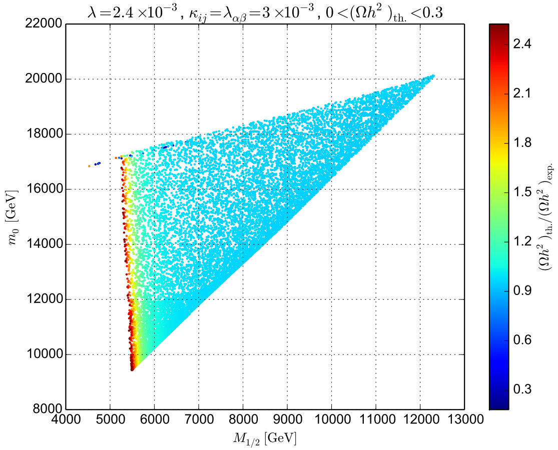
- Altered RG running $\Rightarrow$ gaugino masses at low energies lighter than sfermion masses
- EWSB conditions $\Rightarrow$ physical solutions satisfy $m_0 > M_{1/2}, A_0$
- $\therefore$ MSSM sfermions are very heavy, out of reach of LHC run II
- Conversely, small $\lambda_{\alpha\beta}$, κ_i $\Rightarrow$ light exotic fermions are observable
  - Exotic leptoquarks D_i, e.g. in $p\,p \to t\,\bar{t}\,\tau^+\,\tau^- + E_T^{miss} + X$, $p\,p \to b\,\bar{b} + E_T^{miss} + X$
  - Charged and neutral inert Higgsinos $p\,p \to Z\,Z + E_T^{miss} + X$, $p\,p \to W\,Z + E_T^{miss} + X$, $p\,p \to W\,W + E_T^{miss} + X$

CP-even Higgs Mass



- Split spectrum $\Rightarrow$ large logarithms contribute to m_h
  - Small exotic couplings $\Rightarrow$ corresponding logarithms small
  - Mainly due to $\tilde{t}$'s
- Standard $\overline{\text{DR}}$ calculation is inaccurate
- Solution: use EFT calculation (using SUSYHD now, cross checked with FlexibleHiggs prototype)
- $m_h \sim 125$ GeV obtained over large part of parameter space

Dark Matter Relic Density: Higgsino LSP

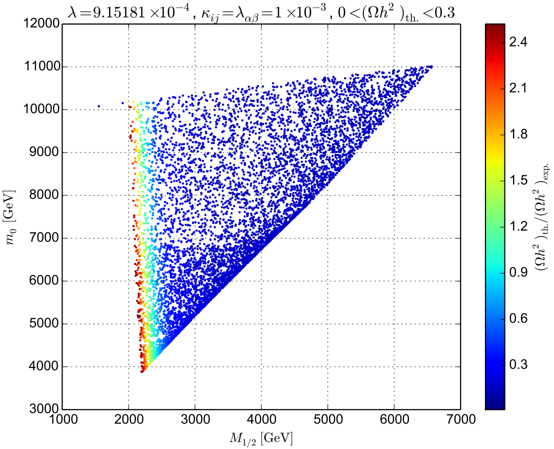


- For Higgsino LSP,

$$\Omega h^2 \sim (\Omega h^2)_{\text{obs}} \left(\frac{\mu_{\text{eff}}}{1\ \text{TeV}} \right)$$

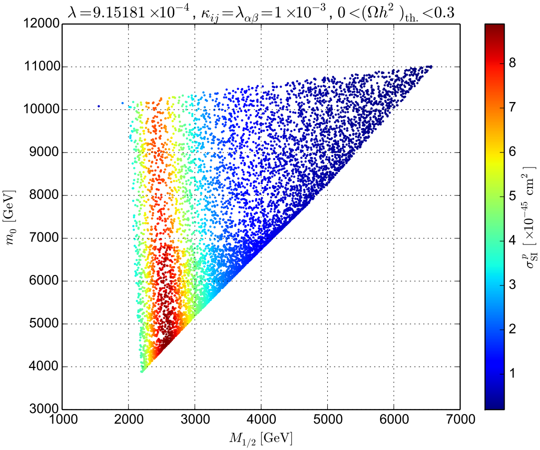
- Mainly co-annihilations $\tilde{\chi}_i^0\, \tilde{\chi}_1^\pm \to \bar{f}_1\, f_2$, $\tilde{\chi}_1^0\, \tilde{\chi}_2^0 \to f \bar{f}$
- Requires $m_{\tilde{\chi}_1^0} \sim 1$ TeV Higgsino
- $M_{1/2}$ must be large ($\gtrsim 6$ TeV) to suppress bino component
- Universal gaugino masses at $M_{\text{GUT}} \Rightarrow$ all gauginos are heavy, e.g. $m_{\tilde{g}} \gtrsim 5$ TeV

Dark Matter Relic Density: Mixed Bino-Higgsino LSP



- Alternative: mixed bino-Higgsino LSP, e.g. $m_{\tilde{\chi}_1^0} \sim 300$ GeV
- Need $M_1 \sim \mu_{\text{eff}}$ for large mixing
  - $M_1 < \mu_{\text{eff}} \Rightarrow$ pure bino, Universe overclosed
  - $M_1 > \mu_{\text{eff}} \Rightarrow \tilde{\chi}_1^0$ light Higgsino LSP, underabundant DM
- Mainly pair annihilation, e.g. $\tilde{\chi}_1^0 \, \tilde{\chi}_1^0 \to \bar{f} \, f$
- Much lighter $M_{1/2} \Rightarrow$ can also have $\tilde{g}$ within reach at run II and HL-LHC

Direct Detection



- Strong constraints from LUX limits on σ_{SI}
- $\sigma_{SI} \propto$ (product of Higgsino, bino components)
- $\therefore$ highly mixed bino-Higgsino LSP $\Rightarrow$ large σ_{SI}
- Very close to LUX limit, would be immediately observed at XENON1T
- Pure Higgsino LSP $\Rightarrow$ small bino component (+ heavy), σ_{SI} is safely below LUX limits
- But still detectable at XENON1T

Summary

- E_6 inspired models can resolve the Little Hierarchy problem of MSSM
- Simplest variants, e.g. E_6SSM, faced with several issues (Z' limits, multiple discrete symmetries ...)
- Considered well-motivated extension, SE$_6$SSM, with exact custodial symmetry
- Heavy Z' $\Rightarrow$ sfermions out of LHC reach, but observable exotic fermions, gauginos
- DM relic density can be fitted by MSSM-like neutralino
  - Higgsino LSP ($\Rightarrow$ heavy spectrum)
  - Mixed bino-Higgsino LSP ($\Rightarrow$ observable gauginos)
- Direct detection limits $\Rightarrow$ strong constraints, easily observable at XENON1T

Thank you for listening!